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Summary on incorporation and test of new components in the relevant ESM

Introduction

The objectives of COMBINE WP1 on carbon and nitrogen cycles are:

- To deliver new carbon and nitrogen cycle components in existing state-of-the-art ESMs
- To include terrestrial emissions of methane in order to evaluate their with feedback with climate change
- To assess and evaluate the new components and hence constrain interactions and feedbacks

This deliverable reports on the work undertaken to fulfil task WP1 T1.1: “*Incorporate new Earth System components into ESMs*”. In the first phase of the project, the new components that have or are being implemented in ESMs include: land-use change, prognostic land and ocean nitrogen cycle, permafrost, wetlands and fire. Note that, according to the project plan, not every component is going to be implemented into each ESMs

Summary

This report details the implementation and testing of Earth system (ES) components in the relevant project ESMs. Most of the required component coupling has been completed although for technical reasons some coupling has been performed into the offline land-surface model of the ESM in question (see Table 1). Full coupling to the ESM in this case is underway. Where a coupling has not yet been achieved, reasons for this are given. A description of progress by modelling group follows.

<i>Model</i>	<i>Process</i>	<i>Fully coupled</i>	<i>Offline coupled</i>	<i>Not yet coupled</i>
HadGEM	Land Use	X		
	Land N		X	
	Ocean N			X
	Permafrost		X	
	Wetlands CH ₄	X		
	Fire	X		
IPSL-ESM	Land Use	X		
	Land N		X	
	Ocean N	X		
	Permafrost		X	
	Wetlands CH ₄		X	
COSMOS	Land Use	X		
	Land N	X		
	Ocean N	X		
EC-Earth	Land Use	X		
	Permafrost			X
	Wetlands CH ₄			X
CNRM	Land Use	X		
NorESM	Land Use		X	
	Ocean N	X		

Table 1. Summary of status of coupling of ES components in relevant project ESMs.

i. METO (including University of Bristol). Model: HadGEM

At the start of the project, the HadGEM2-ES model included the dynamic global vegetation model TRIFFID, but without explicit treatment of time-varying land use. There was no representation of fire or the N-cycle (land or ocean). Frozen and unfrozen soil moisture was represented, but only to a depth of 3m and not including any interaction between organic content and physical properties. Wetland extent was diagnosed and a preliminary simulation of CH₄ emissions from wetlands was enabled.

Land Use. A scheme was developed and implemented into HadGEM2-ES to enable the physical and biogeochemical effects of time-varying anthropogenic disturbance. An aggregate fractional coverage of crop and pasture is provided as a time-varying input. Within a grid box tree and shrub PFTs are excluded from this fraction allowing natural grasses to grow and represent “crops”. Abandonment of cropland removes this constraint on trees and shrubs but we do not specify instant replacement by these woody PFTs, but rather their re-growth is simulated by the model’s vegetation dynamics. If woody vegetation cover reduces because of a land use change, vegetation carbon from the removed woody PFTs goes partially to the soil carbon pool and partially to a series of wood products pools. These wood products pools have turnover rates of 1, 10 and 100 years and are not sensitive to environmental conditions. The fraction of vegetation carbon directed into the wood product pools is proportional to the ratio of above ground and below ground carbon pools ((leaf carbon + stem carbon)/root carbon). Distribution of disturbed biomass into the different carbon pools depends on the vegetation type. Other aspects of land management, such as wood harvest and shifting cultivation (repeated disturbance and re-growth) are also believed to create CO₂ fluxes due to land-use, but data on these within-grid-cell transitions are not yet used.

The biophysical impacts of land use change include the direct effect of changes to surface albedo and roughness due to land-cover change and also changes to the hydrological cycle due to changes in evapotranspiration and runoff (Figure 1). The model has been run with historical land use data based on the HYDE database v3.1 (Klein Goldewijk et al. 2010) and harmonized for use in CMIP5 by Hurtt et al. (2010; downloaded from <http://luh.unh.edu>). Figure 1 shows global temperature change in simulations with only a subset of climate forcing agents, such as GHG-only, land-use only or natural only. The physical impact of land-use can be seen as the difference between the black line (pre-industrial control run) and the pink line (land use change forcing only). From this first simulation it appears that land-use is having a marked mid-20th century cooling effect on climate, possibly due to changes in land-surface albedo. However, the signal to noise ratio of such simulations is low and this result may not be statistically significant. The robustness of this signal will be investigated by extending these simulations to include an ensemble of 4 land-use simulations.

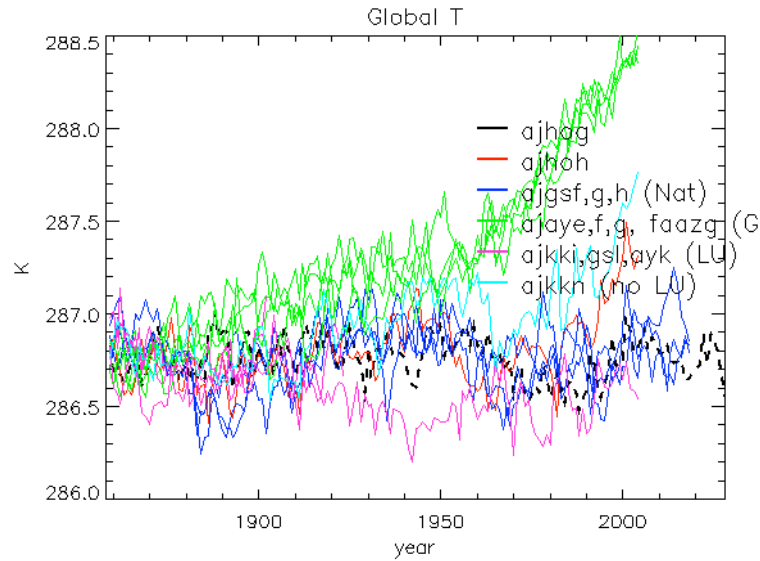


Figure 1: Global temperature simulations for 20th century due to various forcing agents, such as GHG-only, land-use only or natural only. Note particularly, black line (pre-industrial control run) and pink line (land-use).

Nitrogen. Schemes to represent the terrestrial nitrogen cycle have been implemented in the offline land-surface component of HadGEM, JULES. The vegetation nitrogen scheme, FUN (Fisher et al. 2010) and the soil nitrogen scheme, ECOSSE (based on Bradbury et al. 1993) have been coupled together in JULES. Work to implement this into HadGEM is not yet underway until a decision is taken whether to do this work in HadGEM2 or HadGEM3. Technical coupling of JULES into HadGEM3 is not expected to be difficult as it has already been achieved for earlier (non-N) versions of JULES. Development of the ocean biogeochemistry model, HadOCC, to include Nitrogen cycle is not yet underway. A similar decision is required to choose the future version of ocean biogeochemistry to couple to HadGEM. Once this decision is made, development work will recommence.

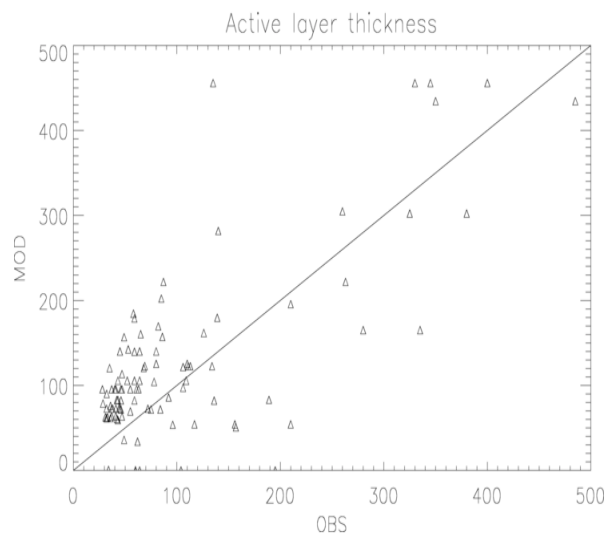


Figure 2: Active layer thickness (cm) from model and observations. JULES simulations include deeper and more well resolved soil. The original 4 layers to 3m depth are increased to 70 layers to 10m depth. Modelled active layers tend to be a bit high (i.e. deeper active layer) but overall agreement is encouraging.

Permafrost. Several permafrost developments have been implemented and tested offline in JULES. Deeper soil column, better vertical resolution of soil levels and the inclusion of the physical properties of organic soils have all been tested (Figure 2). Work has been hampered by the difficulty of finding suitable offline driving (meteorology) data and evaluation data, but pan-arctic comparison of active layer depth with observations is encouraging (Figure 3). Similar analysis on HadGEM2-ES output is underway.

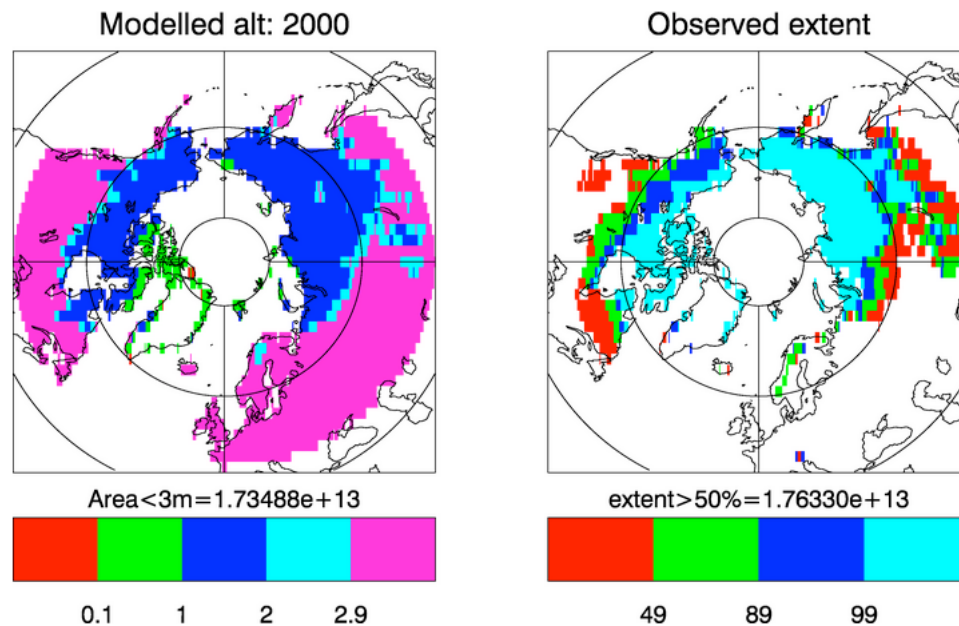


Figure 3: Left: Active layer thickness (ALT) in JULES on a 1-degree resolution (driving data=observational analyses). Compare the area where ALT is less than 2.9 m with the right plot. Right: observed extent as a percentage of permafrost within the grid cell. Although this is not a like-for-like comparison, the simulated area of permafrost agrees well with observed extent.

Wetlands. Wetland extent is simulated in HadGEM2-ES along with a preliminary scheme to simulate methane emissions from wetlands based on simulated soil carbon as substrate. Testing in coupled mode showed that past changes in land-use affected the model's ability to recreate changes in wetlands/methane substrate, as there is no sub-grid treatment of soil carbon. The model was further developed to use a fixed ancillary file of soil carbon as substrate and the time evolution of wetland methane emissions in historical and future simulations is now possible.

However, it is not clear if using soil carbon as a substrate for methane production is the best option. Ongoing analysis (U. Bris) of a more detailed methane model, LPJ-WHyMe (Wania et al. 2009) is underway and is examining the methane production and transport by processes such as ebullition and diffusion. Methane production from root nodules may mean that NPP is a better proxy for substrate than soil carbon although HadGEM2 does not yet simulate an explicit wetlands plant functional type of vegetation.

Fire. Fire is being implemented in HadGEM2-ES in collaboration with scientists from

INPE (Brazil). The scheme currently simulates burned area and fire spread rate, but does not yet simulate interactively fire emissions or intensity. The scheme has been implemented and tested but is still undergoing some model calibration.

A fire plume-rise model has also been implemented which allows simulation of the injection height of fire emissions (including aerosols) into the atmosphere at the correct altitude. At present this scheme is separate from the fire occurrence model. When the fire intensity and emissions module is complete this will form an interactive coupling to the plume model.

ii. CNRS. Model : IPSL-ESM

The land nitrogen cycle was modeled, developed and integrated into the ORCHIDEE model. Hereafter, we refer to the O-CN model as the ORCHIDEE model integrating the nitrogen cycle as well as the associated parameterization. Ocean nitrogen cycle was already part of the PISCES ocean biogeochemistry model.

O-CN (Zaehle and Friend 2010; Zaehle et al. 2010) is developed from the land surface scheme of Earth System model of the Institut Pierre Simon Laplace, ORCHIDEE (Krinner et al. 2005), and has been extended through representation of key nitrogen cycle processes. O-CN simulates the terrestrial energy, water, carbon, and nitrogen budgets for discrete tiles (i.e., fractions of the grid cell) occupied by up to 12 plant functional types from diurnal to decadal time scales. O-CN contains representations of the effects of N availability on photosynthetic capacity (including leaf area) and respiration rates, plant and community structure, and soil organic matter decomposition, as well as N losses to leaching and nitrification-denitrification related N emissions, and considers reactive N inputs from biological N fixation, atmospheric deposition, and fertilizer applications. Another version of ORCHIDEE has been developed so as to account for the arctic ecosystems and permafrost dynamics.

In view of the evaluation of the modeled biogeochemical cycles, we have first performed an evaluation of the reference version of the ORCHIDEE model (Krinner et al. 2005). The evaluation relies on a set of performance metrics that we have proposed so as to quantify the ability of climate-carbon coupled models to reproduce key processes of climate-carbon cycle interactions. These new metrics contain multiple time scale constraints based upon the (1) long-term CO₂ trend, i.e., the global carbon budget, (2) seasonal cycle of CO₂, (3) inter-annual variability of the CO₂ growth rate forced by ENSO climate anomalies, and (4) sensitivity to climatic variations. This work, based on Cadule et al. (2010), defines the evaluation principles that will be used for the new versions of ORCHIDEE integrating the latest developments (e.g., nitrogen cycle, permafrost, wetlands, and fire).

Based on this foundation work we are in the process of completing the set of metrics by identifying new datasets and defining the associated evaluation criteria. In that context, we started the evaluation of the O-CN model on global scales. Towards that objective, we have performed control pre-industrial simulations to reach equilibrium of the carbon pools. We have also performed simulations on the historical period and future period to evaluate how the nitrogen cycle would change the C allocation within plant biomass. Note that control simulations were only performed in off-line mode (i.e., forced with observed climate, e.g. CRU climate dataset). Online simulations

(i.e., in which the climate is simulated) require code parallelization, to be developed later in the project.

During this period, we also largely improved the representation of soil processes. Two points have been developed. First, the N limitation on litter and soil decomposition has been improved by merging the two modules, which were previously independent and caused artificial N limitation on nitrification and denitrification. Then, we added microbial processes acting on the soil carbon mineralization, within the soil decomposition module. Soil microorganisms are the main drivers of soil C mineralization and the old version did not represent soil microorganisms explicitly. In the actual version, an explicit microbial pool is represented.

iii. MPG. Model: MPI-ESM (COSMOS)

In the MPI-ESM ocean model, simplified nitrogen cycle existed in older non-parallel model version. No Nitrogen cycle was available in the land-surface model, JSBACH.

Ocean nitrogen: The nitrogen cycle was implemented into the latest version of HAMOCC used in the ECHAM6/MPIOM MPI-ESM (COSMOS) on a massively parallel supercomputer. The oceanic nitrogen cycle now includes N_2O , NO_3 , N_2 , and NH_3 . Processes include denitrification in oxygen depleted areas (in water and sediment), annamox, and nitrogen fixation by cyano bacteria.

Land nitrogen: Nitrogen has been implemented as a limiting nutrient into JSBACH, which means that the land N cycle is now also part of the coupled model (ECHAM6/MPIOM). During the reporting period the cycling of nitrogen has been fully implemented into JSBACH, including the coupling to the cycling of carbon in JSBACH. Technically this meant to complement all existing pools for organic carbon by a sister nitrogen pool, and to add two additional pools, one to represent mobile nitrogen in plants, and the other for mineral nitrogen (ammonia, nitrous oxide) in soils. Adopting a demand-supply ansatz, the implementation is straightforward. For the description of nitrogen fixation and denitrification existing model approaches have been taken over. To model nitrogen leaching a homogeneous distribution of soil mineral nitrogen is assumed across the soil water column. Nitrogen deposition is implemented as forcing.

The model has been tested in offline mode (driven by climate data input) against published site data for NPP (Net Primary Productivity), plant nitrogen content, and plant N uptake. Despite the simple approach, there is reasonable correlation. Apparent modeling alternatives have been checked to be of minor importance.

Of special interest to COMBINE is the simulation of N_2O emissions. For this purpose a special sub-model has been implemented and tested. Implementing the full coupling via N_2O emissions into the ECHAM6/MPIOM ESM is under way.

The developed model has been used in offline mode to study nitrogen limitation for the historical period (1850-today), and into the future, following an A1B-szenario based on climate input data from the ENSEMBLES study by Roeckner et al. (2010). The simulations show no nitrogen limitation of vegetation growth until about 1950, but rises to about 12% reduction in vegetation carbon in the year 2100. The dynamics

of nitrogen limitation is most clearly visible in the behaviour of soil mineral nitrogen (SMN): For forests SMN decreases until the mid of the 21st century. This conforms with the expectation from the progressive nitrogen limitation (PNL) hypothesis (Luo et al., 2004; Reich et al., 2006), stating that under CO₂ rise enhanced growth leads to a lack of nitrogen in forest soils. This limitation relaxes during the second half of the 21st century because – as our simulations demonstrate – the significant climate warming found in the A1B scenario leads to an enhanced heterotrophic respiration in soils, whereby a significant amount of the nitrogen formerly bound in organic biomass is once more mineralized.

Concerning simulated N₂O emissions, box model calculations show that they reproduce very well the observed rise in atmospheric N₂O since 1850 (see Figure 4). Using the same box model we could also show that the feedback between N₂O emissions and induced greenhouse warming is negligible, not only today, but also during the 21st century.

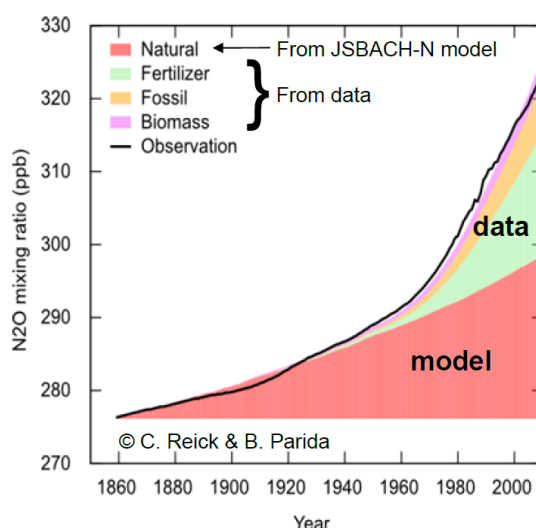


Figure 4: Results from box model calculations for atmospheric N₂O concentration using N₂O emissions from JSBACH.

iv. KNMI. Model: EC-Earth

The model considered in this study at KNMI is EC-Earth, a fully coupled AOGCM. At the starting point of the project we used Version 2.1, including the following components: IFS cy31r1 (atmosphere) with HTESSEL (land surface) / NEMO v2 (ocean) / LIM v2 (sea ice) / OASIS3 (coupler). The land surface scheme HTESSEL uses a tile approach, partitioning each grid cell into 6 tiles of bare soil, high as well as low vegetation, intercepted water, and shaded and exposed snow. Dominant vegetation types and coverage, leaf area index and background albedo are prescribed, and constant throughout the year. Dynamic phenology is not included and land cover is fixed for all model simulations.

In this period we have prepared the relevant model components of the EC-Earth model to accept land cover changes, as well as with the preparation of the required input data itself, and parameter adjustments.

Model-specific time series of land cover changes were constructed for a historic simulation (1850-2009) as well as the 4 RCP scenarios (2005-2100) of the CMIP5 standard experimental protocol. These are based on GLCC land cover characteristics (Loveland et al. 2000), time series of changing crop and pasture extents (LUH – land use harmonization project, Hurtt et al. 2010) and a map of potential vegetation (Ramankutty and Foley 1999). Due to the model set-up, new maps of low and high vegetation coverage and dominant type of vegetation were prepared for two different model resolutions T159 and T799.

Several tests to isolate vegetation specific albedo values were made in order to reassemble albedo matching the new land cover. New albedo fields are based on MODIS and ERBE products and vegetation specific total albedo is extracted by singular value decomposition of albedo-LAI correlations within latitudinal bands of 20 degrees. Further test are made with first separating vegetation and soil albedo and then applying the above-described approach only on the vegetation albedo.

Tests to include the simulation of a variable leaf area index (LAI) into HTESSEL are made, building on earlier work done at ECMWF. Model specific i/o structure had to be adjusted to allow for input and output of leaf area index fields. Further understanding and improving the representation of the main processes governing land-atmosphere interactions at global to local scales might also improve the skill of decadal forecasts. The impact of using a LAI climatology based on MODIS products in comparison to previously used constant tabular values is tested with respect Evaporation, 2 meter temperature, total precipitation, surface sensible heat flux, and Surface latent heat flux as follows:

The experiment set-up consists of the following nine-year runs (2000-2008):

- A) Control runs with the previous, constant leaf area index based on tabular values based on land cover,
- B) Runs with a leaf area climatology following a fixed phenological cycle derived from MODIS data,
- C) Runs with LAI data for each specific year, also based on MODIS.

Each experiment A), B), C) consists of ten members, forced by prescribed SST data. Improved potential predictability as investigated here would be characterized by a gain in the squared correlation coefficient (coefficient of determination), constructed from the ten members for the different seasons spring, summer, autumn, winter, and comparing experiment A) with B) and A) with C).

Further, the coupling of EC-Earth to the dynamic vegetation model LPJ-Guess is prepared. At this stage this comprises several sensitivity tests of the land surface scheme (HTESSEL) to modeled input from LPJ and vice-versa, as well as work on the coupler and model set-up. This work is still ongoing.

EC-Earth specific maps of dominant high and low vegetation type, and vegetation coverage, and albedo were prepared for the period 1850 to 2100 in decadal steps (Figure 5). From 2000-2100 four different sets are available for the four different RCPs according to the CMIP5 protocol.

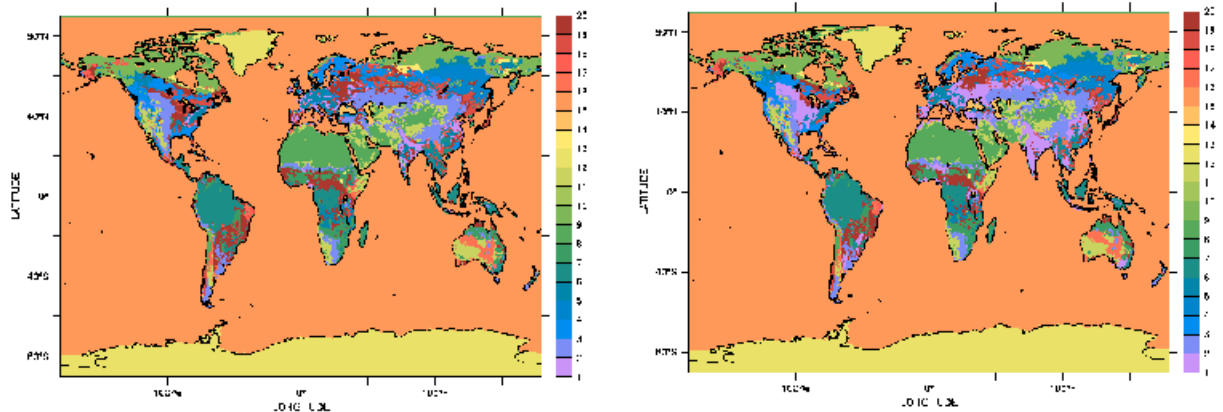


Figure 5: Dominant type of vegetation for 1850 (left) and 2000 (right) for EC-EARTH.

Especially over Eastern Europe and the central U.S., a strong decrease in forest takes place between 1850 and 2000. On the one hand this is due to increasing agricultural area, but also due to increases in wood harvest and logging. There are only few places in the world, where agricultural area decreases between 1850 and 2000.

As part of this set of new land cover fields, monthly albedo fields are provided that are adjusted to the changing vegetation (see Figure 6). Unlike other studies that report an overall increase of albedo due to increase of low vegetation, we find increases mainly in the Northern hemisphere, while in the Southern Hemisphere the change in albedo due to changing land cover is very small, or even negative (i.e. albedo decreases).

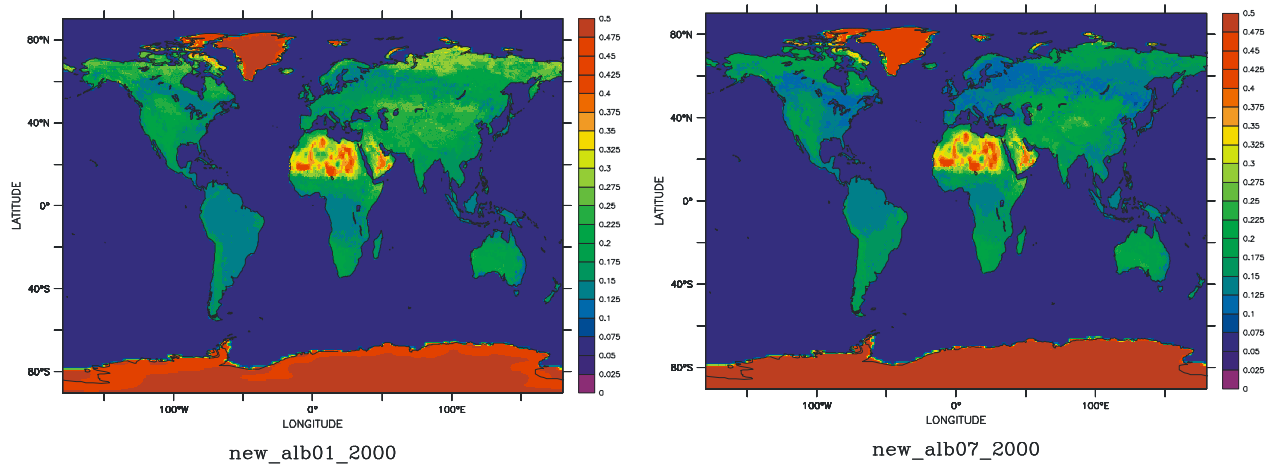


Figure 6: Vegetation-adjusted albedo fields for January (left) and July (right) 2000.

First plots of preliminary potential predictability runs show a stronger correlation coefficient for the individual seasons than when an averaged over the whole year. Further, the correlation coefficient is smaller over land. So far, only marginal differences between the control run and the LAI climatology run are found. However, it has to be noted that these are preliminary results, and runs with LAI data for specific years will follow and indicators will be further discussed and revised.

v. CNRM. CNRM-CM

At the beginning of the reporting period a preliminary version of CNRM-CM5 global coupled model was available. This model has been developed and extensively validated by MF-CNRM and CERFACS. It is currently used by MF-CNRM to run CMIP5 centennial experiments and by CERDACS to run CMIP5 decadal experiments.

Since the beginning of the project, the new surface-atmosphere exchange module SURFEX developed at MF-CNRM has been introduced in CNRM-CM5. It computes the exchanges of heat (radiation, conduction, convection), moisture, momentum and carbon dioxide between the earth surface and the atmosphere. SURFEX also includes a Surface Boundary Layer model to determine the temperature, wind and moisture of the first levels of the atmosphere. SURFEX can be run either in a coupled mode in which case the atmospheric forcing is provided by the host atmospheric model, or in a standalone mode where the atmospheric drivers are derived from observations.

vi. U.Bergen. NorCLIM / NorESM.

As starting points served for the ocean the MICOM-HAMOCC coupled physical biogeochemical ocean model on isopycnic coordinates (for shared memory OpenMP computer architecture) as described in Assmann et al. (2010) (Figure 7). For the land component, starting points where the land biosphere models LPJ and NCAR CLM3.5. At the beginning of the project we were starting to phase out our former carbon cycle climate model BCM-C (Tjiputra et al. 2010) in favour of the new NorESM Earth system model (using the new NCAR CAM and CLM atmosphere and land surface modules as developed by the NCAR communities for CCSM4 and CESM1.0).

The MICOM-HAMOCC physical biogeochemical ocean model was migrated from a shared memory OpenMP system to a distributed memory MPI computing architecture (on the Cray XT4 “Hexagon” at Bergen). The stand-alone ocean model was embedded in the NorESM Earth system modelling framework, so that we run for stand-alone runs the NorESM but with atmospheric data forcing for the ocean model. The land surface model NCAR CLM4 was installed on “Hexagon” as well.

The nutrient (nitrate and phosphate) and also carbon riverine delivery data according to the Global News 1 data set (Seitzinger et al. 2005, Harrison et al. 2005a, b, and Beusen et al. 2005) were distributed on the grid of the new MICOM-HAMOCC model (mpi version) for the configuration (grid geometry) of NorESM by redistributing the respective point sources for the respective tracers to the nearest neighbour grid points.

The land modules CLM3.5 and CLM4 were tested in a data driven (atmospheric forcing) configuration. UiB did not plan originally to work on the N cycle on land, however, CLM4 includes an interactive N cycle (N limitation of primary production) and therefore we will have this part included. We will use the land use scheme foreseen for CLM4 in simulations as soon as it becomes publicly available.

The riverine matter delivery was successfully tested in the Max Planck ocean general circulation model MPIOM-HAMOCC5 (in z-coordinates) in two externally funded

publications (Bernard et al., 2010a; Bernard et al. 2010b, revised version under review). The riverine N input point sources are shown in Figures 8. The delivery of the nutrients and its effects on ocean deficiency and greenhouse gas production will be studied in sensitivity experiments as soon as the spin up is successfully finished.

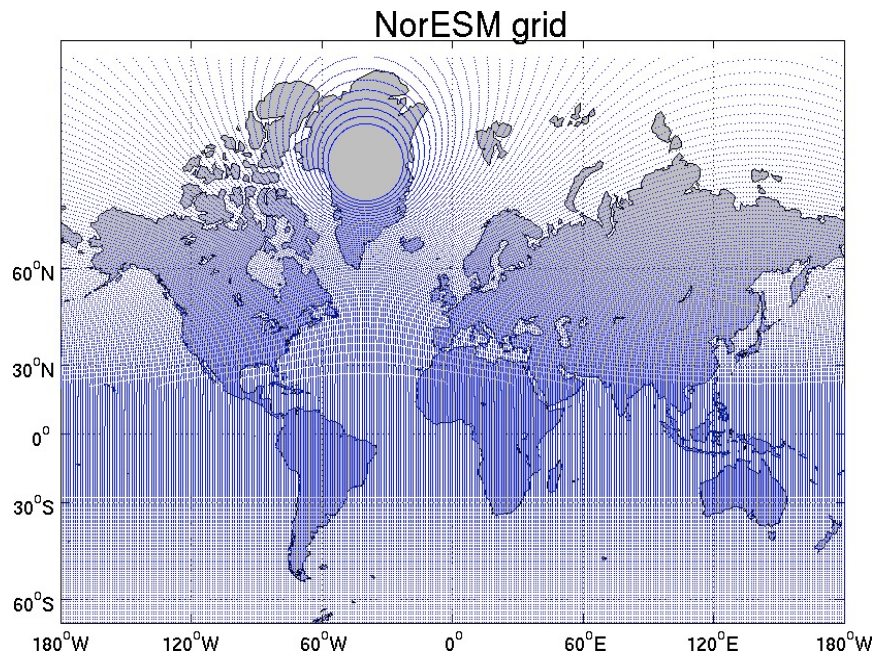


Figure 7: Overview of the ocean model grid of MICOM-HAMOCC for the Earth system model NorESM. (Diagram compiled by C Bernard, UiB)

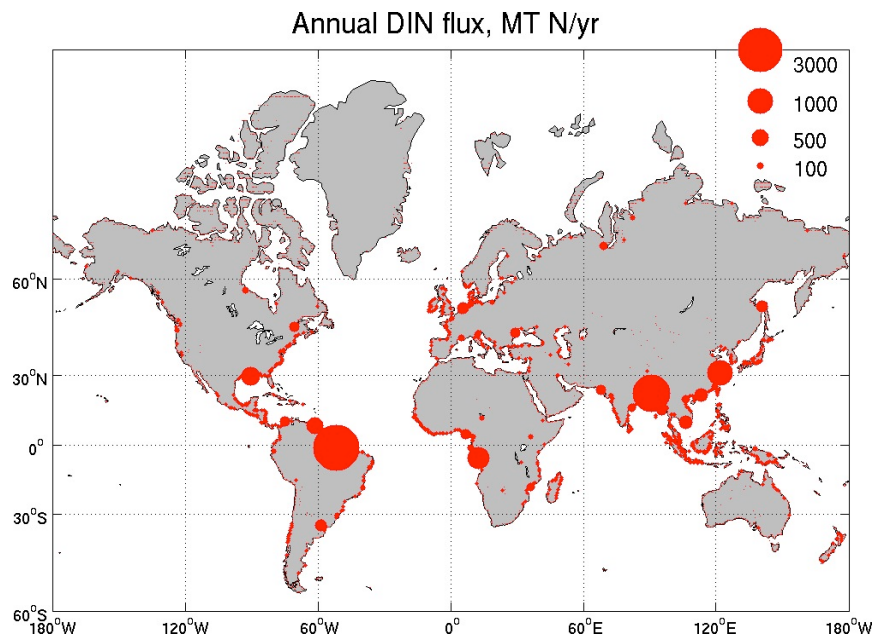


Figure 8: Annual dissolved inorganic nitrogen delivery to the ocean from rivers (in megatons N yr^{-1}) according to the Global News 1 data set (Seitzinger et al. 2005, Harrison et al. 2005a, Harrison et al. 2005b, and Beusen et al. 2005). (Diagram compiled by C Bernard, UiB)

Concluding comments.

The coupling of most of the required ES components into the relevant project ESMs is now mostly complete, with the final work underway or planned. WP1 can now move into the next phase, where each ESM will be set up to couple together and run all of the new sub-components implemented in this first phase. We will report on this work in deliverable D1.2 at end Month 30.

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